Hazard Assessment of Debris-Flow Prone Watersheds in Cubatão, São Paulo State, Brazil

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Research Article

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Abstract

In Brazil, research related to the occurrence and prevention of debris flows is incipient when compared to the extent of the impacts caused by the phenomena. There is a need for more studies that consider their susceptibility and hazard, especially in areas that are environmentally and socioeconomically vulnerable. This study aims at assessing debris-flow hazard in the Rio das Pedras watershed, in Cubatão (São Paulo State, Brazil), based on a set of different physiographic parameters (geomorphological, morphometric, geological) and the application of empirical models. The hazard assessment was based on: (i) the evaluation of the history of events in the region; (ii) the identification of the geomorphic controlling factors; (iii) the estimation of the magnitude of a potential event and, (iv) the identification of the elements at hazard. The results show that a debris-flow event in Rio das Pedras would more severely impact the Anchieta Highway (SP-150), the gas pipeline GASAN, the oil pipeline OSSP, and the districts Pinhal do Miranda and Cota 95. The results showed the relevance of geomorphological and geological parameters in estimating the magnitude of debris runoff for defining the danger in watersheds susceptible to the occurrence of debris flows.

Keywords: Serra do Mar, Hydrogeomorphic processes, Empirical model, Magnitude, Forensic geomorphological analysis

1 Introduction

The occupation of areas prone to natural disasters is a recurrent process in human history, especially in regions with high population density (Alcántara-Ayala 2002; Alvalá et al. 2019; Burton & Kates 1964;; Kahn 2005;). In mountainous regions, the record of natural disasters is frequent, especially hydrogeomorphic processes, which main controlling and initiation factors in tropical areas are, respectively, relief and rainfall (Rickenmann & Zimmermann 1993; Takahashi 2001; Yang et al. 2021).

Debris flows are one of the most destructive hydrogeomorphic processes in Brazil and in the world (Kahn 2005; Álvala et al. 2019). These phenomena occur as dense flows, transporting large amounts of material (from soil to large rock blocks) along drainages paths, with great impact power and large radius of destruction (Hungr et al. 2014; Rickenmann & Zimmermann 1993). The occurrence is primarily associated with exceptionally high-intensity rainfall, in areas characterized by steep slopes and with a large altimetric gradient (Hungr et al. 2014; Takahashi 1991; Varnes 1978).

Hazard assessments are a great instrument to identify and delineate the most impacted areas by debris flows (Corominas et al. 2014; Costa 1984; Egashira, et al. 1997; Fiebinger, 1997; Jakob, 2005; Jakob & Hungr, 2005; Takahashi, 1981; Takahashi 2009). Among the most commonly used methodologies are those based on morphometric parameters (Corrêa et al. 2021; Chen & Yu 2011; De Scally Slaymaker & Owens 2001; Nery 2017; Wilford et al. 2004) and on empirical equations (Cabral et al. 2021; Chang et al. 2011; Fiebieger, 1997; Hungr, et al. 1984; Kanji 1997; Martinez and Garcia, 1999; Massad, 2002; Petracheck & Kenholz, 2003; Rickenmann, 1999; Takahashi, 1991). In Japan, mapping of risk and hazard of debris-flow prone areas are based on combination of parameters, such as morphometry, back-analysis of historical events and on empirical equations (Japan Ministery of Land, Infrastructure and Transport, 1988).

In Brazil, through the GIDES Project (Strengthening the National Strategy for Natural Risks and Disasters, 2018), a debris-flow susceptibility mapping methodology was established based on the use of topographic data, morphometry, and historical analysis of debris flow events (CPRM, 2013; Facuri & Picanço, 2020; GIDES, 2018). While this methodology is valuable for hazard mapping, the practical applicability in decision-making in urban planning studies, as well as in avoiding loss of life and severe damage is yet to be proved.

The aim of this study is to propose a debris-flow hazard assessment methodology, based on the analysis of past events, identification of the main controlling factors, estimation of the magnitude of potential future events, as well as on the identification of the elements at hazard. The Rio das Pedras watershed, in Cubatão (São Paulo

state), is chosen as test-site, due to the extensive history of events in the municipality, as well as due to the environmental and socioeconomical vulnerability of the region.

2 Study Area

The Rio das Pedras watershed has an area of 1.39 km², an altimetric amplitude of 650 meters, and the main channel has a length of approximately 1.7 km (Figure 1). The catchment is chosen as the test-site due to the morphometric characteristics, recurrence of events, and the large volume of on-channel material (rock boulders, woody debris). Moreover, the Anchieta highway (SP -150), pipelines (GASAN and Petrobras OSSP) and residences are located in the watershed's limit, which can be impacted by potential future events.

Cubatão is home to a large industrial and petrochemical complex, extending along the valleys of the Mogi and Cubatão rivers. The industrial facilities, especially those located near the foothills of the mountain range, are frequently at risk of being affected by periodic events of landslides, debris flows, and flash floods. The slopes in the region show clusters with high population density, mainly consisting of irregular occupation with precarious building standards.

Nine debris-flow events have been recorded in the central and eastern stretch of the Serra do Mar hillslopes in Cubatão (Cabral et al., in prep), most notably at the oil refinery region in 1985, 1994 and 1996. The 1994 event paralyzed the refinery's activities for a week, causing U$ 40 million in losses (Kanji et al. 2007; Massad, 2002; Massad et. al 2003; Massad, 2009).

The watershed is located in the "Coastal" geomorphological province, at the Serra do Mar subzone, in the subsystem of festooned scarps with concave amphitheaters (Hasui & Sadowsky, 1976). The geology of the Rio das Pedras watershed is composed of the Precambrian rocks, consisting predominantly of ophthalmic and stromatitic migmatites, schists, phyllites, quartzites, and granites (Tatizana et al. 1987) (Figure 2).

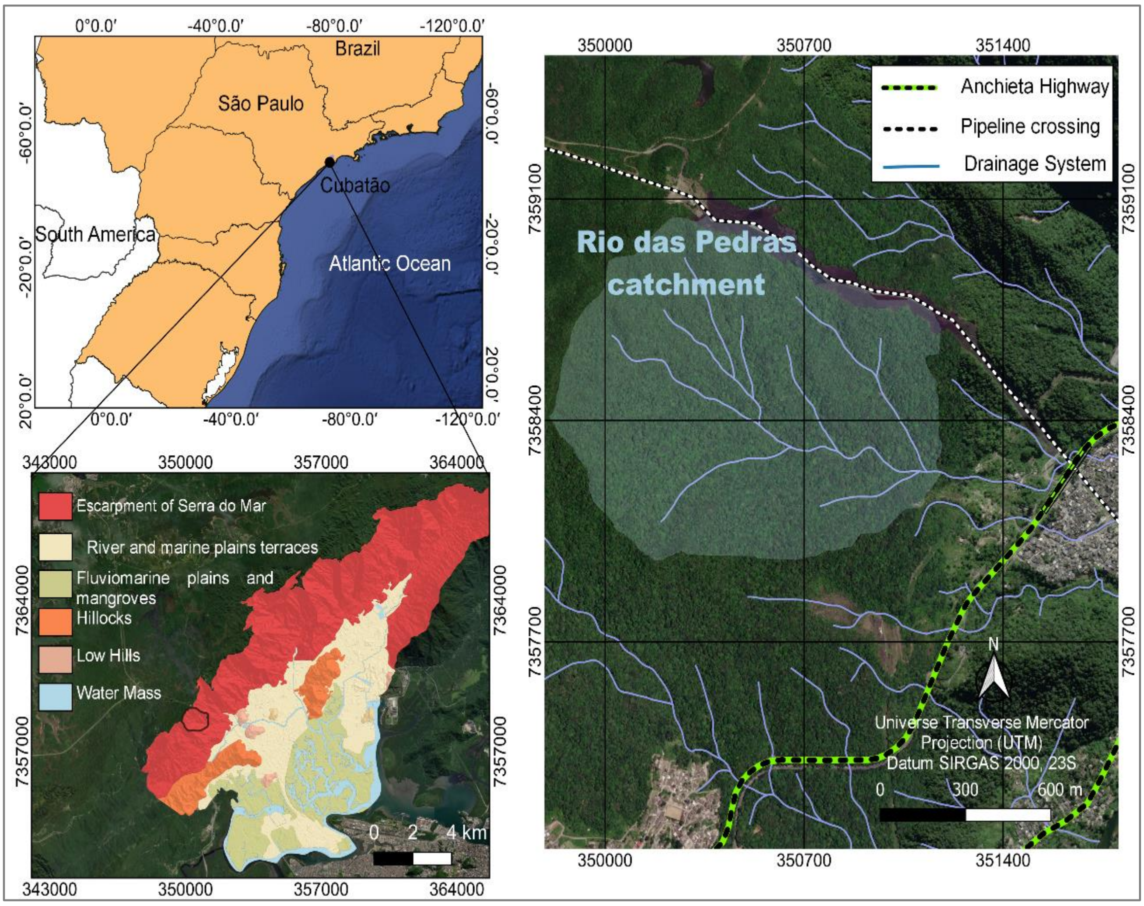

Figure 1 Rio das Pedras watershed (Cubatão, São Paulo) (right). In the upper left corner, the location of the study area. In the lower left corner, the geomorphological context where the watershed is inserted.

Two major lineaments cut through the study region: the Cubatão Fault Zone and the Clastic Belt (Sadowsky 1974). The Cubatão fault zone extends along the southeastern coast of the Mogi and Cubatão river valleys. The Cubatão Lineament separates two distinct blocks : in the north, the Juquitiba block with a predominance of stromatitic migmatites, with SW dip direction (where the Rio das Pedras watershed in located); in the south, the Coastal Block is composed of ophthalmic migmatites, with NE dip direction (Sadowsky 1974).

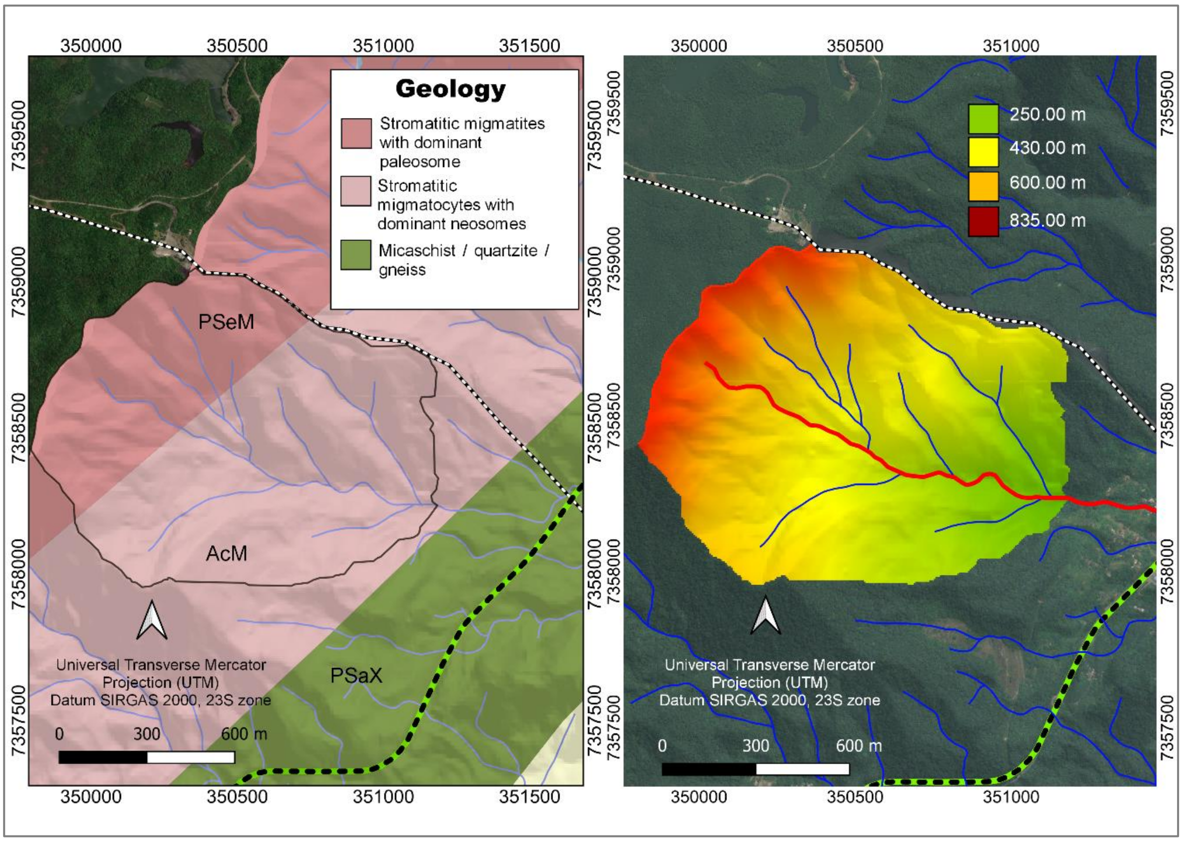

Figure 2 Geological map of the Rio das Pedras watershed (left) prepared by the Mineral Resources Research Company (CPRM). Hypsometric map of the watershed (right) produced by CPRM.

3 Material and methods

The methodology used in this work (Table 1), is based on the application of four steps: (i) survey of the history of recurrence of events in the study area, (ii) mapping of geomorphological conditions, (iii) estimation of the magnitude of a possible event in the watershed, and, finally, the (iv) identification of the elements at hazard .

Table 1 Debris-flow hazard assessment

Steps	Actions
1	Analysis of historical events
2	Analysis of geomorphological conditions
3	Magnitude estimation
4	Hazard assessment

The first step in the hazard assessment was to collect data regarding debris-flow events in the study area, to estimate the recurrence of these events. We assume that the factors that caused extreme events in the past may generate new ones in the future (Van Westen 1993; Guzzeti et al. 1999). The second stage concerns the geomorphological analysis of the watershed, to characterize the main triggering agents the occurrence of eventual mass movements. The third step is the estimation of the magnitude based on the application of

empirical equations of volume, run-out distance, velocity and time of arrival in the deposition area (Kanji et al. 2003; Massad, 2002; Rickemann, 1991; Takahashi, 1991). The fourth step is hazard recognition, where the elements that are susceptible to damages related to debris flows are identified.

3.1 Historical events in the catchment

The debris-flow events that have occurred in the watershed are shown in Table 2, based on Gramani (2001) and Massad (2002). Moreover, based on these events, as well as other in the region of Cubatão, Tatizana et al. (1987) established rainfall thresholds (Figure 3) for landslides and debris-flow initiation. According to Tatizana et al. (1987), a debris flow is triggered when the 72-h accumulated rainfall is over 120 mm, and the peak intensity is over 40 mm h^{-1}.

Table 2 Selection of debris flows events in the Rio das Pedras watershed (Cubatão - SP). Source: adapted from Gramani (2001) and Massad (2002).

	Location	Year	Area (km²)	Triggering Rainfall	Velocity (m/s)	Volume (m³)
1	Rio das Pedras, Cubatão, SP	1988	1.39	25 mm/h - 135 mm/24h	N/D	N/D
2	Rio das Pedras, Cubatão, SP	1944	1.39	0 mm/h - 214 mm/24	10	$3x10^5$
3	Rio das Pedras, Cubatão, SP	1996	1.39	18 mm/1h	10	$1,6x10^4$

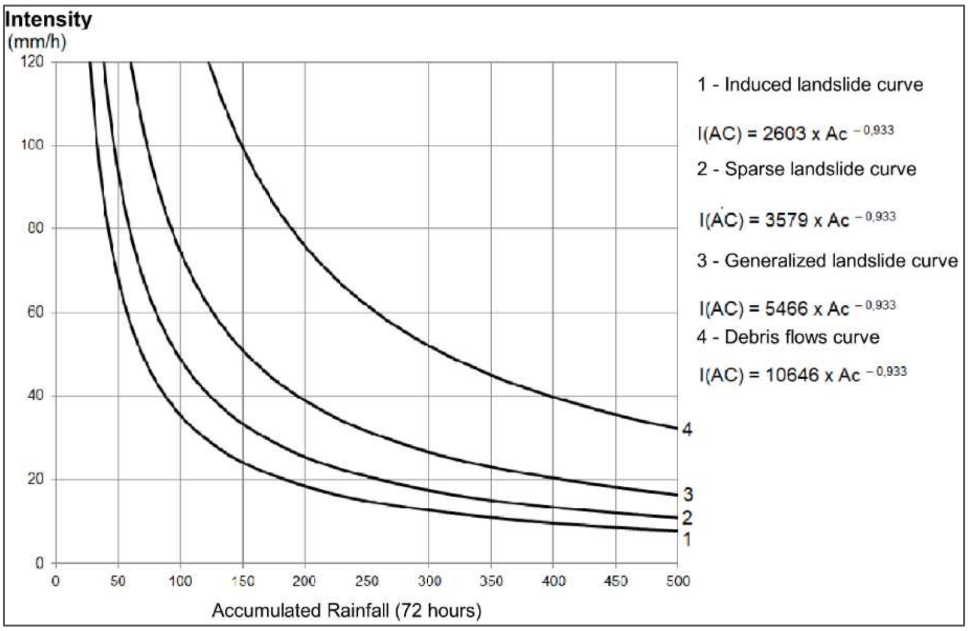

Figure 3 Correlation between precipitation and mass movement (Tatizana et al.1987)

3.2 Mapping of the geomorphological and geological conditions

Fieldwork was carried out in September 2019 to seek evidence of past debris flows in the watershed, as well as to characterize the conditioning factors that trigger the phenomenon. The past occurrence of debris flows has very specific geomorphological and geological features such as: a) Deposits in the deposition area of the watershed characterized by granulometric inversion; b) Presence of large rock boulders in downstream reaches of the channel.

Regarding the characterization of conditioning factors, the flows can be of primary origin (originating on the slopes) usually caused by the occurrence of rotational landslides on steep slopes, providing unconsolidated material for the main drainage ready to be transported (Cruden & Varnes, 1996). Or secondary origin (originating from drainages), triggered from the collapse of material accumulated in natural dams or accumulated without cohesion along the drainage bed (Takahashi 1981).

Thus, the evaluation of geomorphological parameters such as the altimetric gradient of the watershed, degree of carving and amount of material in the main drainage, the slope angle of the slopes, and the presence of talus deposits in the deposition area is important to evaluate the potential of hazard the occurrence of a possible debris flow.

3.3 Magnitude Estimation

The empirical equations applied in the estimation of the physical parameters of debris flow at Serra do Mar are based on Kanji et al. (1997); Massad (1997); Rickenmann (1999); Takahashi (1991). The estimated parameters are peak discharge, magnitude, and run-out distance.

3.3.1 Peak discharge

The peak discharge equation that best fits the study area is the one from Kanji et al. (1997); Massad (2002); Takahashi (1991); according to and (Equation 1).

$$qt = \frac{2}{(1-C)} \cdot A \cdot I_1 \quad (1)$$

Where A is the watershed area (km²), I_1 is the intensity of the accumulated rainfall (mm/h) in the hour before the event and c is the concentration of solids by unit volume.

c is based on Takahashi (1991) equation:

$$c = \rho_0 * \frac{tg\theta}{(\delta-\rho_0)\,.\,(tg\emptyset - tg\theta)} \qquad (2)$$

Where θ is the average slope, ρ_0 is the specific weight of the slurry (water + sediments), δ is the specific weight of the granular material and ϕ is the angle of internal friction of the granular material.

3.3.2 Magnitude

Based on past events at Serra do Mar, Massad (2002) proposed the magnitude equation for the mountain range:

$$V_S = \frac{(1-\eta)\cdot A_e \cdot A' \cdot e}{1-p} \quad (3)$$

Where η is the average porosity of the soil of the hillslopes, A_e corresponds to the landslide area in relation to the total watershed area (*A*', in m²). For these parameters, Massad (2002) proposed that for debris flow at Serra do Mar, on the coast of the São Paulo state, the average depth of landslides (*e*) are 1 m (Tatizana et al. 1987; Wolle, 1988;), η of 40%, p of 15% and A_e of approximately 9%, according to Massad (2002).

3.3.3 Run-out distance

Kanji (2003) established the upper limit of the distance covered by the debris run by the following equation:

$$\frac{\mathrm{H}}{\mathrm{L}} = 1{,}87 \cdot \mathrm{Q}^{-0{,}146} \quad (4)$$

Where *H* is the altimetric gradient of the ramp covered by the debris run (in meters), ***L*** is the horizontal distance covered by the debris run (in meters), and ***Q*** is the volume of material mobilized during the event (in cubic meters).

3.3.4 Velocity

In estimating the peak velocity, as it is an independent parameter of the height variable (h) of the advance front of the debris run, since there is no recent event record to estimate it, the equation that best suits the study area is Rickemann (1991):

$$U = 1{,}3.sen^{0{,}2}(\theta).q_{\circ}{}^{0{,}2}.\frac{g}{d50^{0{,}4}}^{0{,}2} \quad (5)$$

Where U = flow velocity (in ms-1); θ = mean channel slope (º); g = acceleration due to gravity (m/s²); *d50* = mean grain diameter (m); and $q_{\circ}$ = flow only of water (estimated in general for a period of 100 years).

4 Results

4.1 Geomorphology

4.1.2 Slope Conditions

In the study area, characteristics and factors favorable to destabilization processes (shallow and planar landslides, falling blocks, erosion) on the slopes were verified.

The vegetation in the area is mostly preserved or in the process of regeneration, which indicates that the state of degradation is not directly responsible for destabilization processes, as the upper third of the watershed is

preserved without signs of anthropic activities. Deposits characteristic of past debris flow events are found, characterized by granulometric inversion (Figure 6-A), in addition to relatively resistant exposed bedrock (migmatites, quartzites, granites) (Figure 6-C), but with a metric fracturing pattern. which could result in a large supply of material for drainage in a scenario of strong impacts.

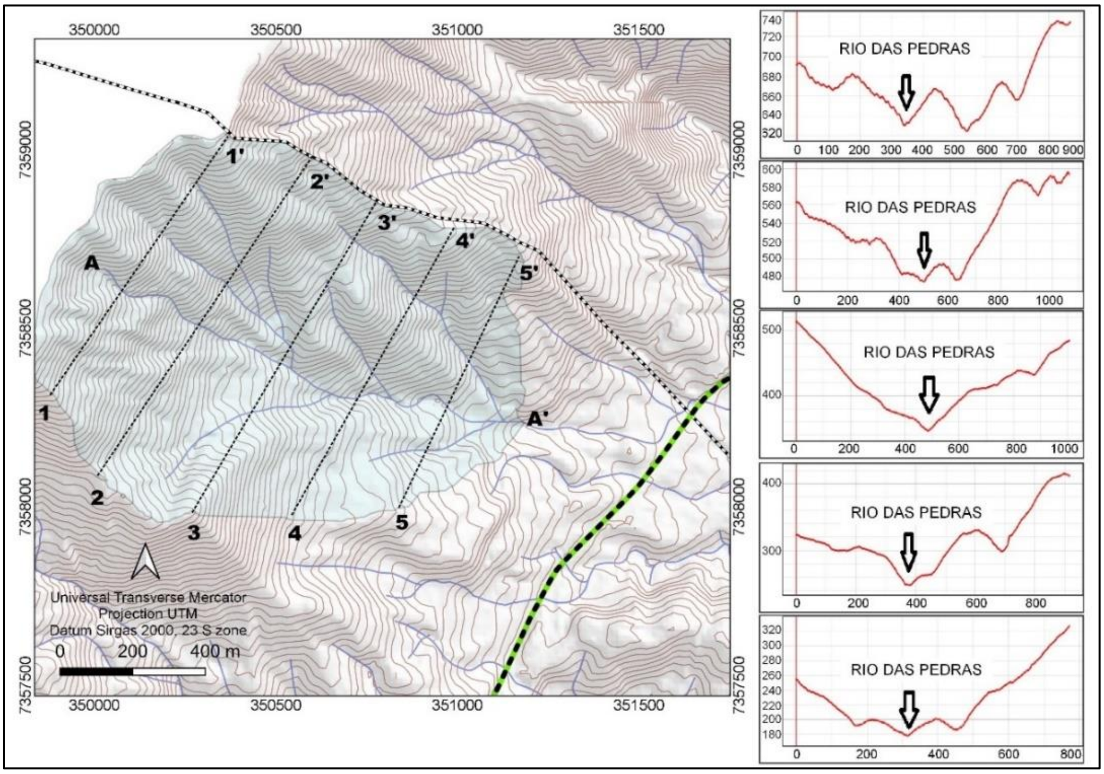

Figure 4: Topographic map of the study area and transversal and longitudinal profiles of the main drainage.

Figure 5: Front view of the slope side tank. A) Eroded deposit with granulometric inversion typology, typical of debris flows; B) Frontal and partial view of an elongated straight slope; C) Highly altered granite and migmatite / slope with signs of recent movement.

4.1.3 Drainage conditions

Drainage channels have a direct influence on the process of formation and development of a debris flow through geomorphological characteristics and associated deposits. The material mobilized in a detritus run does not come only from the slopes, but a significant portion, especially the coarser ones, is incorporated by surface depositions positioned along the drainage (talus, colluvium, alluvium, river terraces and old deposits from past flows).

In the study area, the coverage observed along the main drainage line could be divided into the following types of deposits: a) alluvial terraces of small thickness, varying from 1 to 2 meters, with a small extension, distributed in the final third of the drainage, between the transport and deposition zone. In this portion, there is a predominance of gravel and a coarse sandy matrix. Towards the headwaters, the increase in granulometry is noticeable, in which the terraces start to present a predominance of blocks and boulders of metric dimensions; b) colluvium and residual soils, formed in some portions along the drainage slope; c) coarse alluvium (Figure

7-A, 7-B and 7-C) covering the drainage bed, rework products; d) metric blocks varying from 1 to 5 meters, forming dams from the upper third of the slope (Figures 8-A and 8-B);

Figure 6 Main drainage characterization. A) alluvial terraces with coarse material, ranging from 0.5 to 2 meters and with the presence of residual colluvium; B) coarse alluvium covering the drainage; C) alluvial terraces with coarse material, ranging from 1 to 2 meters.

Figure 7 Main drainage characterization. A) metric blocks imbricated, forming total damming in the drainage line; B) metric blocks forming total dam, with blocks varying from 1 to 5 meters and abundant presence of detrital material.

The surface coverings that are more susceptible to remobilization form an abundant source of material along the drainage, especially in the stretches where the slopes are accentuated and the drainage presents a more acute notching.

The main drainage profile (Figure 9) is represented with its flow development and movement zones, following the premises of Vandine (1996).

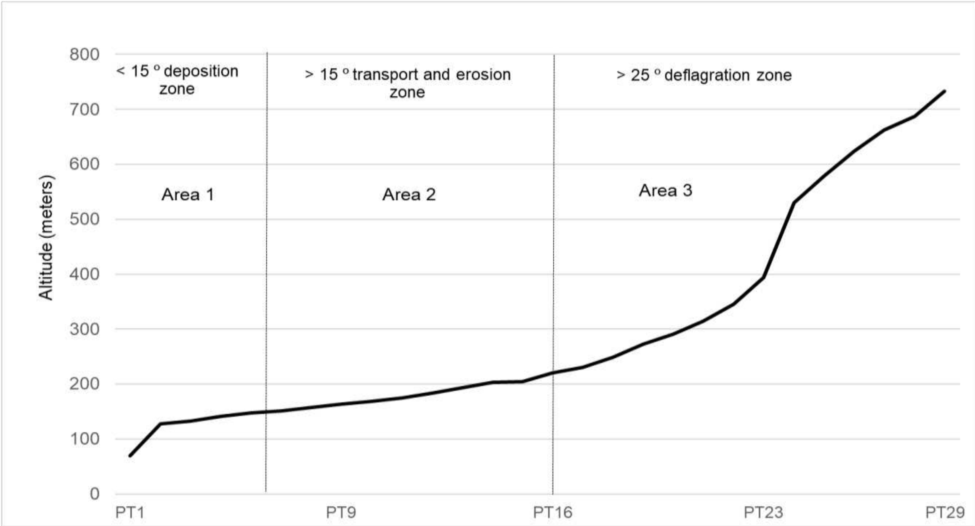

Figure 8 Slope profile of the main drainage of the Rio das Pedras basin.

The slopes in the headwater region present values close to 70°, with reductions to values of 30° up to the limit of the deflagration zone. In the medium slope section, the values are between 25 and 15º, with some abrupt levels recorded. Finally, in the stretch downstream from the 100-meter altimetry level, the slope undergoes smoothing, presenting values below 15º, evidencing the final stretch of deposition.

4.1.4 Natural dams

The natural dams are an important geomorphological indicator in watersheds and consist of an aggravating element in relation to the deflagration of debris flows, their observation in the field is fundamental for the projection of future scenarios. Its origin is conditioned to the clutter of plant material and rocky blocks, responsible for totally or partially blocking the drainage.

Whether in the main or secondary drainages, these dams behave in a way to partially retain the flow, giving rise to a kind of reservoir.

Basically, the increase of water during a rainy event in the system and a drastic increase in the flow, causes the accumulated potential energy to dissipate causing the rupture of these dikes, releasing all the dense flow of contained debris, resulting in numerous debris pulses.

In the study area, of the 17 points that were possible to map, in the main drainage (Figure 10), 3 correspond to partial dams (Figure 11-A), and 14 are total dams (Figure 11-B), that is, they block the entire the main drainage, with bottlenecks and a high degree of carving.

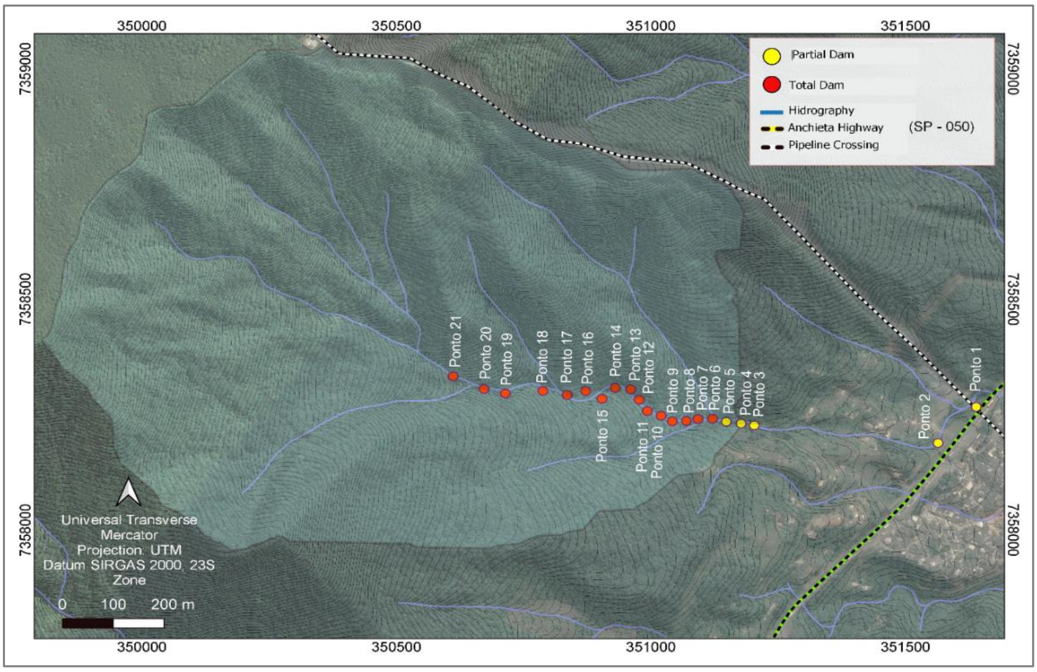

Figure 9 Location of the dams mapped in the main drainage.

Figure 10 Characterization of dams in the main drainage. A) Front view of the partial bus, with blocks varying from 1 to 3 meters and its schematic profile; B) frontal view of the total dam in the main drainage, with blocks varying from 2 to 4 meters, evidence of detrital material and schematic profile.

5 Magnitude estimation

5.1 Peak Flow and Volume

Using peak flow equation 1, adopting a solids concentration (c) of c = 37.6, based on Kanji et al. (1997), the basin area of 1.39 km², the estimated cumulative hourly rainfall intensity was respectively I1 = 40 mm/h, resulting in a peak flow of 538.46 m³/s.

Considering equation 3, the volume of solids that can be transported by a run in the basin, according to a precipitation scenario under the aforementioned conditions, is estimated at approximately 168,000m³.

5.2 Distance Covered (run-out) and Average Speed

The distance covered by the debris flow in the Rio das Pedras basin, according to equation 3, was 1856 meters, considering the upper third of the main drainage as the starting point, in which the main deflagration zone is located (Figure 11).

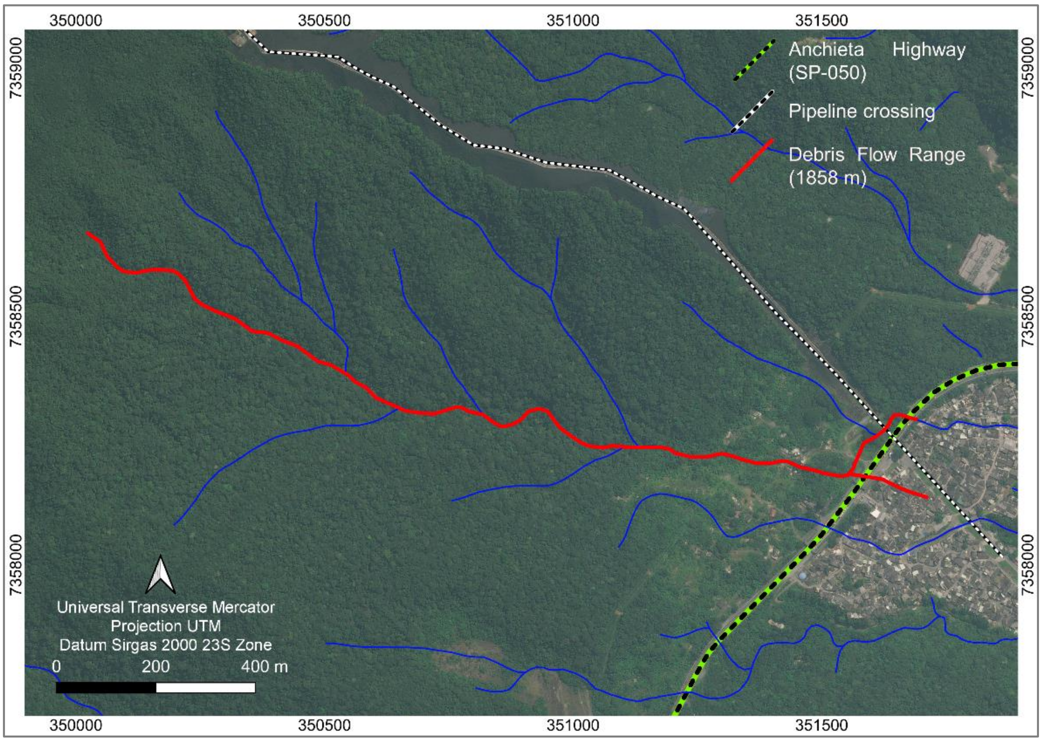

Figure 11 Range of debris flow.

6 Hazard mapping

The mapping of forms of occupation in the immediate radius of the debris flow deposition zone was carried out through fieldwork, in which three main elements at risk were identified: stretch of the Anchieta Highway (SP-150), located in the basin deposition area; the upstream gas and oil pipeline line and the neighborhoods located downstream of the basin. (Figure 12).

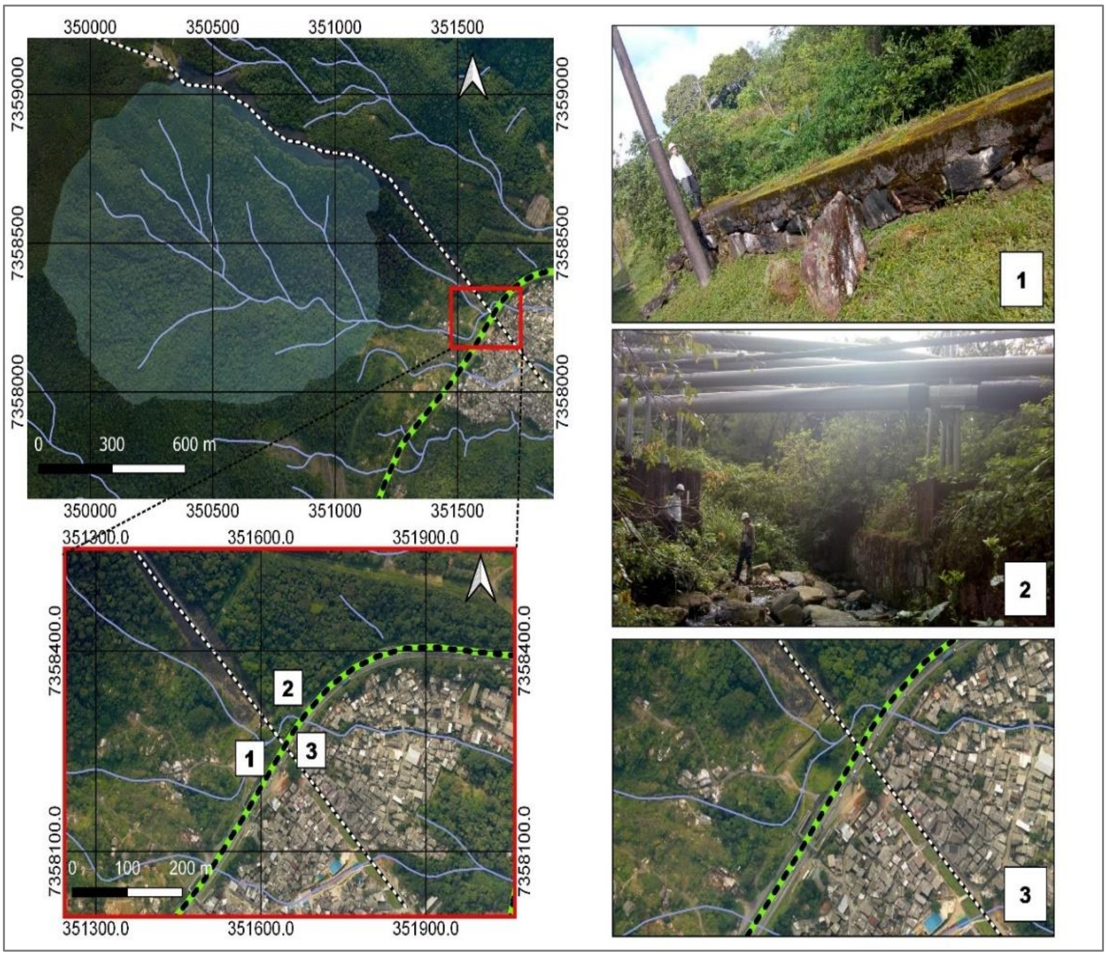

Figure 12 Risk scenarios present in the study area: [1] Wall with the function of protection for the Anchieta Highway (SP-150) for possible occurrences of debris flow, greatly impacted by previous events; [2] ascending pipeline network in possible collision course of eventual debris flows; [3] Cota 95 and Pinhal do Miranda in the deposition area.

Based on the mapping carried out in the main drainage, the deposits found in the deposition area confirmed the past occurrence of debris flows and the estimate of the magnitude through the radius of reach, the two districts located downstream of the main drainage of the hydrographic basin are on the impact route. adding to the aggravating factor that the range of oil and gas pipelines and the Anchieta Highway are also on the direct impact route.

In order to establish the area where the debris can be reached, the values obtained in the design applied by the equations of volume and run-out distance of reach were taken into account, together with the topographical and morphometric characteristics of the deposition area.

In this way, the risk map was generated (Figure 13), where the Red Zone is classified as an area of very risk of impact to a debris flow, this stretch will be most impacted, being the area of greatest impact and deposition of large amount of metric blocks, mud and tree trunks. The Yellow Zone is defined as a high-risk stretch, receiving excess material that crosses the highway, such as mud and smaller rocky and plant material.

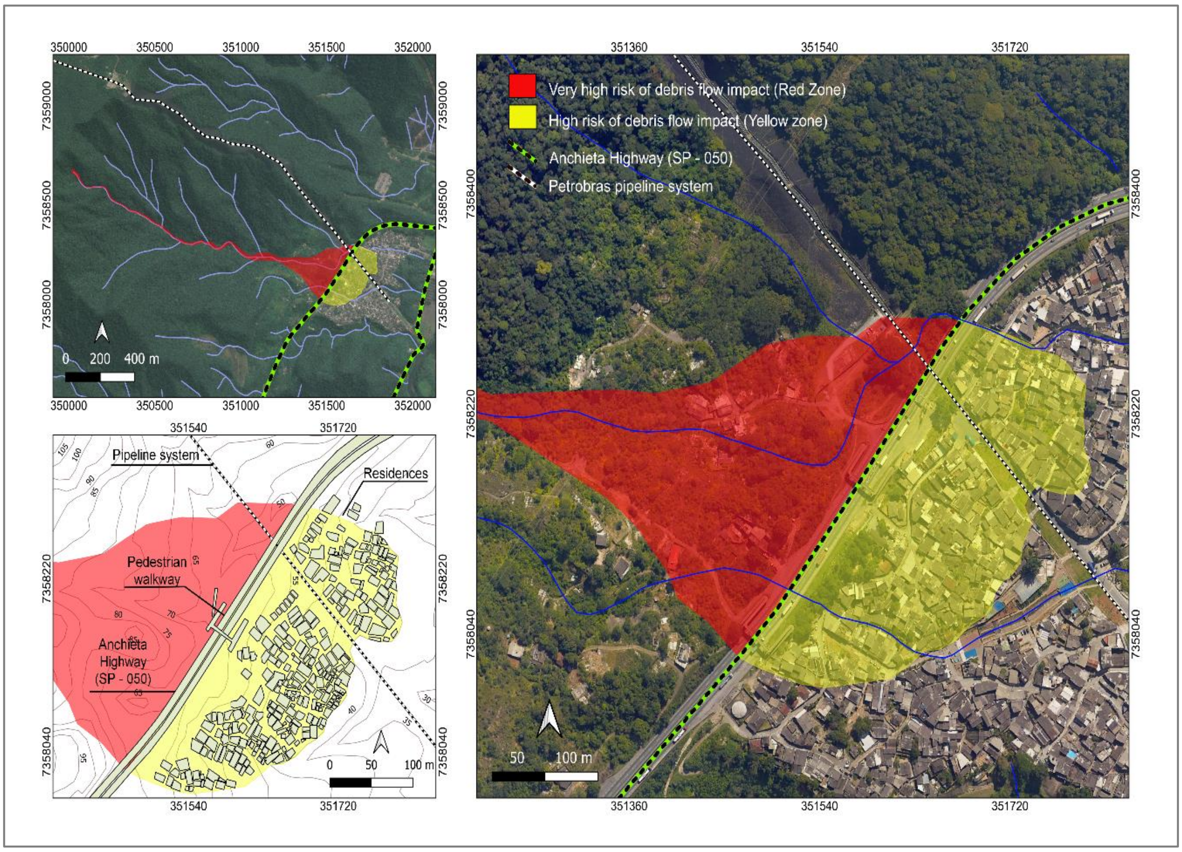

Figure 13 Risk mapping. (Right) Red Zone: very high-risk area to impact from a debris flow; Yellow Zone: high risk area to impact from a debris flow. In the upper left corner, the Rio das Pedras watershed and the representation of the dimensioning of the debris flow in the main drainage to the deposition areas. In the lower left corner is the representation of the risk area and the infrastructures at risk of immediate impact.

8 Conclusions

The application of the methodology considering the hazard assessment in the Rio das Pedras basin in the municipality of Cubatão, identifying its main objects under risk of reaching and estimating their parameters of occurrence and extreme debris flow events proved to be satisfactory.

Based on the phenomenological model adopted and on the evaluation of the slopes and drainage conditions, it can be said that there are conditions for generating debris flows in the main and secondary drainages that drain their waters to the lower third of the hydrographic basin, through a precipitation scenario specific and extreme. Nevertheless, the hazard assessment presents some similarity with the other events that occurred in the same municipality in surrounding watersheds, evidencing a certain relationship and empirical confirmation, especially related to the volume of sedimentary material transported, to the pattern of deflagration and to the displacement of the flow.

These methods showed effectiveness in the assessment of hazard, allowing to define the scope of an eventual debris flow. However, it should be noted that these mathematical relationships are relatively dispersed, that is, they do not exactly summarize the complexity of reality.

Thus, the need for more studies focused on the dynamics of debris flows in mountainous regions and the development of new models and approaches for a better understanding of the phenomenon and its outbreak becomes vital.

Due to the fact that the area presents a high degree of environmental and social hazard to debris flow events, it is recommended in the short and medium term to adopt non-structural measures, such as monitoring and alert systems for automated and integrated mass movement and actions structural structures, such as the installation of containment structures in these more critical sections, such as sabo-type dams, in order to reduce the impact of an eventual debris flow phenomenon.

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Competing interests

The authors declare that they do not have any competing interests.

Data availability

The datasets generated during our study are available from the corresponding author upon request.

Author contributions

Mr. Veloso worked on the development and writing of the manuscript, organized and collected fieldwork data. Dr. Reis organized the fieldwork campaign, contributed with the development and organization of the manuscript. Mr. Cabral contributed to the fieldwork and writing of the manuscript. Dr. Zaine contributed to the writing and organization of the fieldwork and data collection. Dra. Correa aided the collection of fieldwork data and data processing. Mrs. Gramani aided in the fieldworks, collection data and writing the manuscript. Mr Ogura aided in the fieldworks, collection data and organization of the manuscript. Mr. Kuhn aided the organization and writing of the manuscript.